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Research Article

Influence of Wellbore Dogleg Severity on Drilling Friction in Horizontal Wells

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In horizontal drilling, high frictional forces adversely influence operation efficiency. The influence of the rate of change in the overall hole trajectory angle (dogleg severity) is often ignored in the prediction of frictional force in drilling program design, and there is a shortage of quantitative analysis. Aiming at this issue, a mathematical model for computing the radial force caused by axial tension, string bending, and gravity of the string was established. It is found that the axial tension and the gravity of the string are the main forces affecting the radial force of the string, and the bending radial force of the medium-long-radius horizontal well is no more than 14% of the gravity of the string. The influence of dogleg severity on the friction in the vertical, building, and horizontal sections was analysed, and the equations for computing the friction were also established. Based on case analysis, it is suggested that dogleg severity should be kept within a lower limit in the vertical section of horizontal wells with a greater TVD (true vertical depth) because the greater the TVD, the higher the add-on factor related to string tension. For example, in the upper well section with a vertical depth of 3000 m, the add-on factor related to string tension is 0.5, and dogleg severity at 1000 m should be controlled within 0.5°/30 m. Lower building rate should be adopted in the early building section, and appropriately higher building rate can be adopted later. Sliding drilling should be practiced as less as possible provided that target hitting is guaranteed, and combined drilling should be used more. In horizontal wells, dogleg severity at certain point of the horizontal section should be controlled inversely proportional to the drilling drag caused by the subsequent points. The closer to target A (the starting point of the horizontal section), the higher the control requirement for dogleg severity, and it can be appropriately reduced in subsequent well section. If the horizontal interval length L_h is 1000 m and the friction coefficient μ is 0.3, then dogleg severity ϑ should be controlled within 1°/30 m at point A and within 2°/30 m at the middle.

1. Introduction

Well drilling friction includes drag (with axial movement) and torque (with rotation movement) of the drilling string [1]. The higher friction affects the drilling efficiency. The frictional force is calculated with the classical Coulomb's law of friction; that is, the friction is proportional to the contact force between the drill string and the borehole wall, with the proportionality coefficient being the friction coefficient μ [2, 3]. It used to be generally thought that the friction coefficient is a constant and depends mainly on the nature of the two contact materials, especially their surface finish. However, according to modern tribology, the friction coefficient depends not only on the nature of the materials themselves but also on other relevant conditions [4]. In order to facilitate the study, all these factors are generally integrated to the friction coefficient in the calculation of friction [5]. As a result, the major difference between different friction calculation models lies in their different approaches for calculating the contact force between the string and wellbore (also known as the radial force). Depending on whether the influence of string rigidity is considered in the radial force calculation, friction calculation models can be classified into the rigid rod model, the flexible rod model, and the hybrid model. The flexible rod model is also called the rope model [6, 7], which assumes that the drill string lies completely on the lower hole wall and has no rigidity but can transfer torque. The bending resistance of the drill string is ignored in the rope model, making the calculation relatively simple, so it is widely used in drilling engineering. However, some errors exist in the calculation with this model in well sections where the bend rigidity of the string is high, such as the building section and the bottom hole section. In practice, we usually need to modify the friction coefficient to make the calculation more accurate. Although it can satisfy the engineering requirement, this method has to be based on a great amount of drilling experiences. The rigid rod model [8] takes into account the bending resistance of the pipe string, but it is rarely applied independently because of the too large and non-consistent calculation results. In most cases, it is applied in combination with the flexible rod model. The combined model, also known as hybrid model, integrates the advantages of the two models: the flexible rod model is used for the slant section, and the rigid rod model [9, 10] is used for sections where the rigidity of the string is higher, or additional rigid contact force [11] is considered, all to approximate the actuality as much as possible. The gap element method [12] is also a kind of rigid rod model which takes the advantage of modern computer calculation ability. The method makes use of the discretized data volume to analyse the contact scenario of the string and the borehole wall under the complex force regime, offering high calculation accuracy. However, its application in the well site is also limited by the lengthy computation and difficulty in solution convergence. It is generally believed that the friction in horizontal wells is related to smoothness of the borehole trajectory, lubricity between the string and borehole wall, borehole diameter uniformity, and cutting transport efficiency. According to the survey results [13–16], in addition to the above factors affecting the friction, there is also an obvious relationship between dogleg severity and the friction. Researchers [12, 17–19] have studied the influences of the main characteristics of the trajectory, such as profile type, KOP (kick-off point) position, and building rate on drilling friction. But what they would usually do is substituting the actual trajectory data into the friction calculation model and back-calculating the friction coefficient based on the frictional force actually measured. Then, they would examine the pattern of the friction coefficient changing with dogleg severity and qualitatively evaluate the trajectory quality. In general, this approach is an ex post qualitative analysis short of any quantitative feature. In this paper, the influence of dogleg severity, an important metric of trajectory quality, on the friction in horizontal wells is quantitatively discussed. A mathematical model of friction prediction considering the influence of dogleg severity is established. The equation of dogleg severity is studied by analysing the main forces that affect the radial force of the drilling string, which provides a reference for controlling dogleg severity in horizontal drilling.

2. Mathematical Model for Computing the Radial Force

The forces at any point on the drill string mainly include axial tension, the string bending, and gravity of the string. A short section of the string can be roughly treated as an arc, with its radian being θ, which is approximately equal to the overall hole trajectory angle (the dogleg) if the influence of the clearance between the string and the hole wall on it is ignored. In the curvilinear coordinate system established at the midpoint of the string section, the string gravity, axial tension, and string bending force can be decomposed to three directions, i.e., tangential, principal normal, and secondary normal directions (Figure 1). The vector sum of the two normal forces is the radial force exerted by the string. As shown in Figure 1, the string gravity, axial tension, and string bending force all make contribution to the radial force.

2.1. Tension Radial Force. The radial force caused by axial tension is called tension radial force. The axial tension of the drill string can be decomposed into two forces: tangential τ_0 and normal n. Upon mechanical analysis, we know the tension radial force is

$$N_{fd} = \left(F_d + \cong \Delta F_d\right) \sin \frac{\theta}{2} + F_d \sin \frac{\theta}{2}, \qquad (1)$$

where N_{fd} is the tension radial force (kN), F_d is the axial tension of the string above this point (kN), ΔF_d is the incremental axial tension of the string above this point (kN), and θ is the dogleg of the hole section (rad).Both of θ and ΔF_d are very small, so it can be thought that $\sin \theta = \theta$; and upon neglecting the high-order small portions $\Delta F_d \bullet \sin (\theta/2)$, Equation (1) becomes

$$N_{fd} = F_d \theta. \qquad (2)$$

As can be seen from Equation (2), the tension radial force is proportional to the axial tension and the dogleg. During drilling, the drill string is under tension above the neutral point and under compression below the neutral point. The upper part of the string in the vertical section is usually subjected to a greater axial load than the lower part, so a greater radial force may arise even if the dogleg is small in the vertical section. Now, let us take a horizontal case well as an example, where the KOP is at 3000 m and enter the horizontal section at 3400 m (target A). The horizontal section is 820 m long. The tension radial force during tripping is shown in Figure 2, which indicates that in the vertical section, the tension radial force reached 1.2 kN/m during tripping in and 2.95 kN/m during tripping out. Therefore, it is necessary to control dogleg severity in the vertical section.

2.2. Bending Radial Force. The radial force due to the string bending is called the bending radial force. In our analysis, it is assumed that the string is in full contact with the borehole wall, and the contact force is evenly distributed along the drill string. The magnitude of the contact force is F_n, and its direction is in the arc plane. The length of the string is L, as shown in Figure 3.

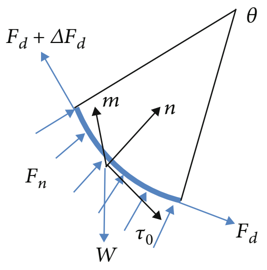

FIGURE 1: Pipe string force and curvilinear coordinate system.

According to the material mechanical deformation energy method, the strain energy U generated by the bending of the drill string can be calculated as follows:

$$U = \int_0^L \frac{EI}{2} \left(\frac{d^2 y}{dx} \right)^2 dx, \tag{3}$$

where E is the elastic modulus (Pa) and I is the cross-sectional moment of inertia (m^4).And the work done by the uniformly distributed load is

$$W = \int_0^L (F_n \cos \beta) y dx. \tag{4}$$

Transforming the coordinate system in Figure 3 into the polar coordinate system will lead to

$$x = R\left(\sin \beta + \sin \frac{\theta}{2} \right), \tag{5}$$

$$y = R\left(\cos \beta - \cos \frac{\theta}{2} \right), \tag{6}$$

where R is the radius of curvature (m), θ is the dogleg (rad), and β is the included angle between the two lines, i.e., the line connecting a point on the string and the center O_1 and the central line (°).

Substituting Equations (5) and (6) into Equations (3) and (4), we will get

$$U = \frac{EI}{16R} \left(4 \tan \frac{\theta}{2} \sec^3 \frac{\theta}{2} + 6 \sec \frac{\theta}{2} \tan \frac{\theta}{2} + 3 \ln \frac{|\sec (\theta/2) + \tan (\theta/2)|}{|\sec (\theta/2) - \tan (\theta/2)|} \right), \tag{7}$$

$$W = F_n R^2 \left(2 \sin \frac{\theta}{2} - \frac{2}{3} \sin^3 \frac{\theta}{2} - \frac{1}{2} \cos \frac{\theta}{2} \sin \theta - \frac{\theta}{2} \cos \frac{\theta}{2} \right), \tag{8}$$

According to the theorem that work is equal to energy, $W = U$, substituting $R = L/\theta$ into the equation, we get

$$F_n = \frac{EI\theta^3 \left(4 \tan (\theta/2) \sec^3 (\theta/2) + 6 \sec (\theta/2) \tan (\theta/2) + 3 \ln \left(|\sec (\theta/2) + \tan (\theta/2)| / |\sec (\theta/2) - \tan (\theta/2)| \right)\right)}{16L^3 \left(2 \sin (\theta/2) - (2/3) \sin^3 (\theta/2) - (1/2) \cos (\theta/2) \sin \theta - (\theta/2) \cos (\theta/2)\right)}. \tag{9}$$

It can be seen from Equation (9) that the radial force exerted by the string in a curved well section is proportional to the cube of the curvature radius, but the equation is too complicated, so let t be equal to the right side of Equation (10), i.e.,

$$t = \frac{\theta^3 \left(4 \tan (\theta/2) \sec^3 (\theta/2) + 6 \sec (\theta/2) \tan (\theta/2) + 3 \ln \left(|\sec (\theta/2) + \tan (\theta/2)| / |\sec (\theta/2) - \tan (\theta/2)| \right)\right)}{16L^3 \left(2 \sin (\theta/2) - (2/3) \sin^3 (\theta/2) - (1/2) \cos (\theta/2) \sin \theta - (\theta/2) \cos (\theta/2)\right)}. \tag{10}$$

If $L = 30$ m, the corresponding θ is the equivalent to dogleg severity ϑ. The relationship between t and ϑ can be numerically calculated, as shown in Figure 4.

It can be seen from Figure 4 that t is directly proportional to ϑ when ϑ is smaller than 20°/30 m. As shown in Figure 5, upon regression, t can be simplified as

$$t = 3.92 \times 10^{-6} \vartheta. \tag{11}$$

The deviation between the regression result and the actual value is shown in Figure 5. The regression error is less than 2% when dogleg severity is within 20°/30 m.

At present, the building rate in horizontal wells is usually lower than 15°/30 m, for which the error of Equation (11) is within 1.1%.

Therefore, for common horizontal wells, the equation for calculating the bending radial force can be simplified as follows:

$$F_n = 3.92 \times 10^{-6} EI\vartheta. \tag{12}$$

It can be seen from Equation (12) that the bending radial force is in direct proportion to dogleg severity. The higher the dogleg severity, the greater the bending radial force.

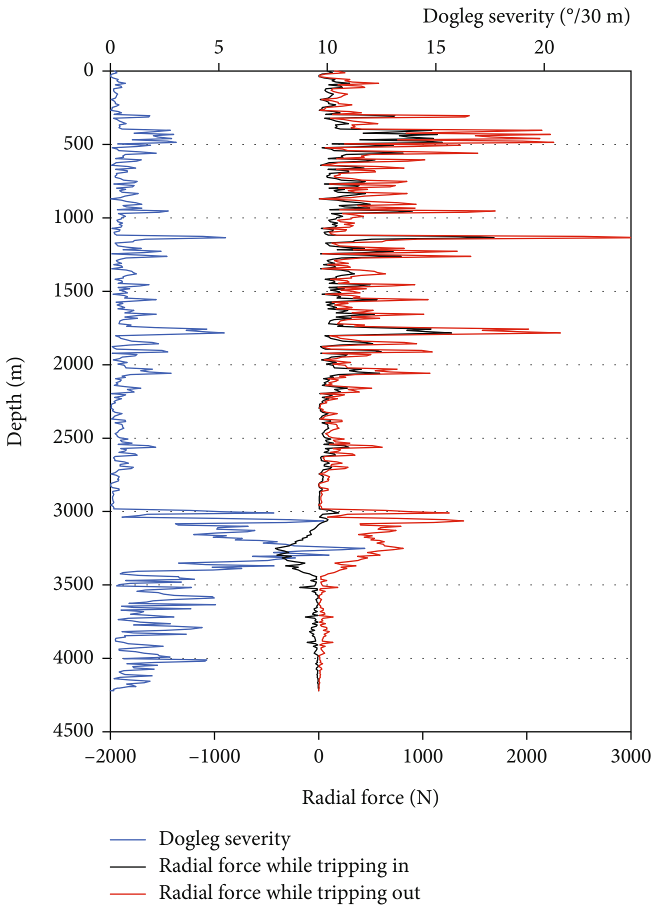

Figure 2: Profile of tension radial force during tripping in a horizontal well.

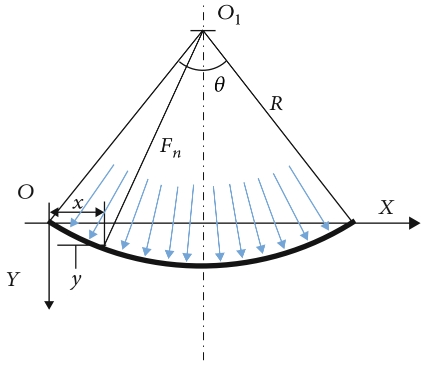

Figure 3: Contact force due to the string bending.

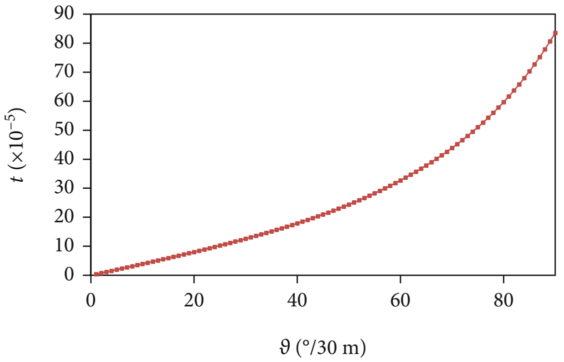

Figure 4: Relationship between t and dogleg severity ϑ.

Suppose k is the ratio of the bending radial force to the weight of drill string; then,

$$\begin{aligned} k &= \frac{F_n l}{ql} = \frac{3.92\times 10^{-6} EI\vartheta l}{K\rho g A l} \\ &= \frac{3.92\times 10^{-6}\times 2.16\times 10^{11}\pi\left(\left(d_o{}^4 - d_i{}^4\right)/64\right)\vartheta}{7.8\times 10^3\times 9.8\pi\left(\left(d_o{}^2 - d_i{}^2\right)/4\right)K} \\ &= 0.699\vartheta\frac{d_o{}^2 + d_i^2}{K}, \end{aligned} \qquad (13)$$

where K is the buoyancy factor equal to $1\,\rho m/(7.8\times 103)$, with ρm being the drilling mud density in kg/m^3, d_o is the outer diameter of drill string (m), d_i is the inside diameter of drill string (m), ρ is steel density (kg/m^3), g is the acceleration of gravity (m/s^2), and A is the cross-sectional area of drill string (m^2).

As can be seen from Equation (13), the ratio of bending radial force to weight of drill string is related to dogleg severity, inside and outside diameters of the string, and mud density. The k values for different diameter drilling pipes are shown in Table 1 if the mud density is 1.5 g/cm^3.

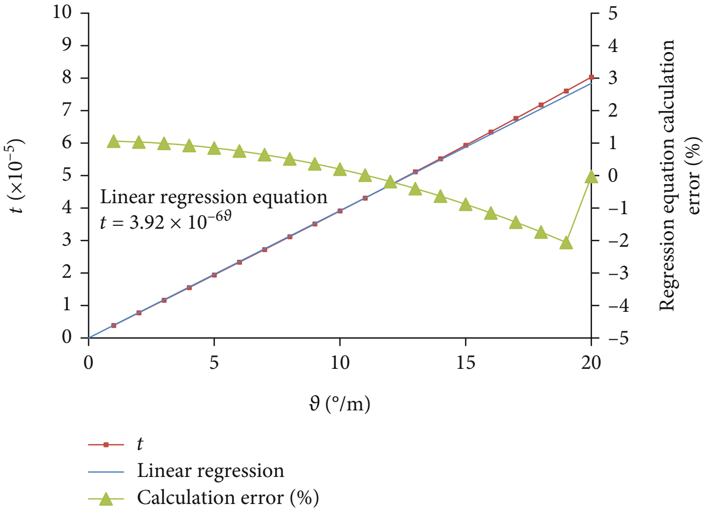

FIGURE 5: The relationship between t and the dogleg ϑ (<20°/m).

TABLE 1: k values of different diameter drilling pipes at different dogleg severity.

Drilling pipes	Outside diameter (mm)	Inside diameter (mm)	k ($\vartheta = 1$)	k ($\vartheta = 5$)	k ($\vartheta = 10$)
Drilling pipe	127	108	0.024	0.120	0.241
Heavy weight drilling pipe	127	76.5	0.019	0.095	0.190
Drilling collar	159	71.4	0.026	0.131	0.262

The bending radial force does not exceed 3% of the string weight if dogleg severity is lower than 1°/30 m. The force is within 14% of the floating weight of the string if the building rate is 5-6°/30 m.

2.3. Gravity Radial Force. The radial force generated by the gravity of the string is called gravity radial force, which is mainly related to the well inclination. The gravity radial force in the slant section is

$$qn = qL \sin \alpha, \tag{14}$$

where q is the floating weight of the drilling string per meter (N/m), L is the length of the string (m), and α is inclination angle of the section (°).

When the dogleg is higher than zero, the gravity of the string is decomposed into the three directions in the curvilinear coordinate system as done in the literature [20]. But the expressions of the forces in the principal normal direction and the secondary normal direction are rather complicated, as shown in

$$q_m = \frac{qL \sin \alpha_1 \sin \alpha_2 \sin (\varphi_2 - \varphi_1)}{\sin \theta}, \tag{15}$$

$$q_n = qL \frac{\sin^2\alpha_1 \cos \alpha_2 - \sin^2\alpha_2 \cos \alpha_1 + \sin \alpha_1 \sin \alpha_2 \cos (\varphi_2 - \varphi_1)(\cos \alpha_2 - \cos \alpha_1)}{\sin \theta \sqrt{2 + 2 \sin \alpha_1 \sin \alpha_2 \cos (\varphi_2 - \varphi_1) + 2 \cos \alpha_1 \cos \alpha_2}}, \tag{16}$$

where q_m is the component of gravity in the secondary normal direction (N), q_n is the component of gravity in the principal normal direction (N), α_1 and α_2 are the well inclination angles at the upper and lower ends of the string section, respectively (°), and φ_1 and φ_2 are well azimuth angles at upper and lower ends of the string section, respectively (°).

For simplification, the contribution of the string gravity to the radial force can be calculated based on the gravity component in the tangential direction, namely,

$$q_{\tau_0} = \frac{qL(\cos \alpha_1 + \cos \alpha_2)}{\sqrt{2 + 2 \cos \theta}}, \tag{17}$$

$$q_n = qL\sqrt{1 - \frac{(\cos \alpha_1 + \cos \alpha_2)^2}{2(1 + \cos \theta)}}. \quad (18)$$

From Equation (18), we know that gravity radial force increases with increasing string weight per unit length and with decreasing the dogleg.

2.4. Radial Force Generated by the BHA. Highly rigid drill collars and stabilizers are generally incorporated into the BHA, generating higher radial force [21–23]. However, it occurs only at the bottom of the well—a very short hole section; hence, no detailed discussion is intended in this paper.

3. Mathematical Model for Controlling Dogleg Severity

Friction affects adversely the operating efficiency in long horizontal wells [24, 25]. In the drilling program design stage, the influence of dogleg severity on drilling friction is normally ignored in predicting the drilling drag and torque, with the trajectory being regarded as an ideal smooth curve. However, in practice, dogleg severity will inevitably occur in the well trajectory. According to the analysis above, the calculation of several forces which affect the radial force of the drill string is related to dogleg severity. The radial force determines the frictional force. Therefore, the influence of dogleg severity on friction has to be seriously considered. The influence in horizontal wells will be examined with a well divided into a vertical section, a building section, and a horizontal section.

3.1. Vertical Section. In the vertical section which is not or only slightly inclined, the weight of the string has little contribution to the radial force, which in this case mainly consists of bending radial force and tension radial force. However, the bending radial force is less than 10% of the weight of the string if dogleg severity is lower than 5°/30 m. But the tension radial force might be great and usually occurs in the upper hole section where the axial tension is great (as shown in Figure 2).

The axial tension of the drill string in the vertical well section can be regarded as the weight of the drill string below the depth of the research well section, which can be expressed as

$$F_d = q\bullet(D - h), \quad (19)$$

where F_d is the axial tension of the string (kN), D is the maximum depth of the string (TVD) (m), h is the depth of the hole section (m), and q is the weight of the string per unit length (N/m).

In fact, the pulling force of the string is not completely equal to the drill string weight; it is also affected by friction and buoyancy. Therefore, the pulling coefficient of the string a is added; then,

$$F_d = q\bullet(D - h)(1 + a), \quad (20)$$

where a is the add-on factor for string tension which can be taken as the ratio of the drag to the string weight below well depth h and can be adjusted based on the specific requirement.

According to Equation (2), converting dogleg severity ϑ to the dogleg θ, we have

$$\theta = \vartheta \frac{\pi l}{30 \times 180}, \quad (21)$$

where l is the length of the string section (m) and ϑ is the dogleg severity (°/30 m).

If dogleg severity of the vertical section is limited to a magnitude for which the tension radial force is smaller than the weight of the string (otherwise the friction would be equivalent to the friction generated by a string lying completely on the lower wall of a horizontal section), then we have

$$q\bullet(D - h)\vartheta \frac{(1 + a)\pi l}{5400} < ql. \quad (22)$$

This relation can be simplified to

$$\vartheta_h < \frac{1718.87}{(1 + a)(D - h)}, \quad (23)$$

where ϑ_h is maximum dogleg severity at well depth h (°/30 m).

It can be seen from Equation (23) that the deeper the horizontal well (TVD), or the longer the lower vertical section, the greater the add-on factor; and ϑ has to be kept smaller. Taking the case well in Figure 2 as an example, the friction in the horizontal section is about 28 tons. In this case, dogleg severity has to be controlled within 0.5°/30 m if the add-on factor in the upper 1000 m vertical section is assumed to be 0.5; for the 1000–2000 m vertical section, dogleg severity has to be controlled within 1°/30 m. Upon doing so, the tension radial force will be smaller than the weight of the string.

3.2. Building Section. The string is subjected to a complex force regime in the building section, and the radial force is great. Firstly, the gravity radial force increases with the increasing well inclination. Secondly, the tension radial force is also higher because both of the compression while tripping in and the tension while tripping out are much greater than those in the horizontal section; the higher dogleg severity also contributes to the tension radial force. Thirdly, the bending radial force is also greater due to the higher dogleg severity. Assuming that the azimuth does not change, all the gravity will act to the principal normal direction; in this case, all radial forces of the pipe string are jointly affected by tension radial force, bending radial force, and gravity radial force. Combined with Equations (2), (12), and (18), radial forces in the bending section can be expressed as

$$q_n = F_d\theta + 3.92 \times 10^{-6} EI\vartheta L + qL\sqrt{1 - \frac{(\cos\alpha_1 + \cos\alpha_2)^2}{2(1+\cos\theta)}}. \tag{24}$$

Again, the case well in Figure 2 is taken as an example. The tension radial force while pulling out in the building section reached 1.5 kN/m due to dogleg severity in the initial orientation. If the drag in subsequent drilling is to be kept within 10 tons, a radial force of 290 N/m would arise at 5°/30 m of dogleg severity (first term in the equation), which is equivalent to 5″ drill pipe weight. Based on Table 1, we know that at 10°/30 m of dogleg severity, the bending radial force is only 26.2% and 24.1% of the string weight for drill collars and drill pipe, respectively (second term in the equation). Therefore, the key to reducing the drilling friction in the building section is to control the magnitude of the tension radial force.

Based on the analysis above and on Equation (24), the following measures should be adopted to control friction in the building section: (1) keep the building rate lower in the upper part of the building section and increase it appropriately in the middle and lower parts. In this way, higher dogleg severity can be avoided in the upper part where the string is subjected to greater forces, resulting in a smaller radial force and hence smaller friction. This is basically what is being performed in the Changqing Oilfield (northeast of China) optimizing the hole trajectory of wells with a long horizontal section [26]. (2) Use less sliding drilling and more combined drilling at a lower building rate to reduce tension radial force and bending radial force and stick to the trajectory-controlling philosophy of "less sliding, more rotating, fine and frequent adjusting" in the building section [25].

3.3. Horizontal Section. Gravity radial force dominates in the horizontal section, and bending radial force is relatively low (Table 1). Consequently, it is also necessary to control the tension radial force in order to control the drilling friction in the horizontal section. Similar to the vertical and building sections, the axial force is rather complex around point A in the horizontal section. Furthermore, the trajectory around point A is critical for hitting the target, where high dogleg severity is likely to occur, and so is the tension radial force. As shown in Figure 2, dogleg severity reached 5.2°/30 m around 3400 m.

Let us assume that the length of the horizontal section is L_H, the floating weight of the string is q, and the friction coefficient is μ. If the axial pulling force at a certain point in the horizontal section is simply taken to be the drilling drag while the string lies on the lower wall of the subsequent part, according to Equation (2), then for the interval L_h, we have

$$F_{dh}\theta_h = (L_H - L_h)q\mu\frac{\pi\vartheta_h l}{30\times 180}, \tag{25}$$

where l is the length of the string section in question (m), F_{dh} is the axial pulling force at horizontal interval h, and ϑ_h is the max allowable dogleg severity at depth L_h in the horizontal section (°/30 m).

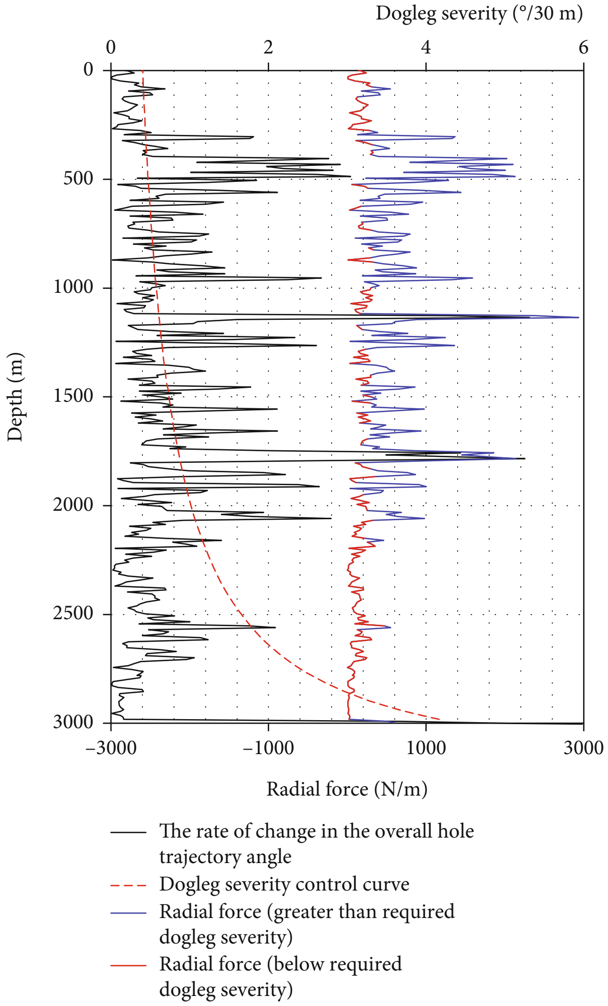

Figure 6: Distribution of whole radial force in the vertical section of a horizontal well during tripping out.

Dogleg severity in the horizontal section has to be properly controlled in order to prevent a dramatic increase of the whole radial force. Let us assume that the ratio of tension radial force to the weight of the string is b. Then, we have

$$F_{dh}\vartheta_h < bql, \tag{26}$$

namely,

$$(L_H - L_h)q\mu\frac{\pi\vartheta_h l}{30\times 180} < bql, \tag{27}$$

namely,

$$\vartheta_h < \frac{1719.7b}{(L_H - L_h)\mu}. \tag{28}$$

It can be seen from Equation (28) that the maximum dogleg severity ϑ_h at L_h of the horizontal section is inversely proportional to the friction in the subsequent section. If the ratio of tension radial force to weight of the string, b, is to be controlled at 18%, L_h is 1000 m, and μ is 0.3, then dogleg

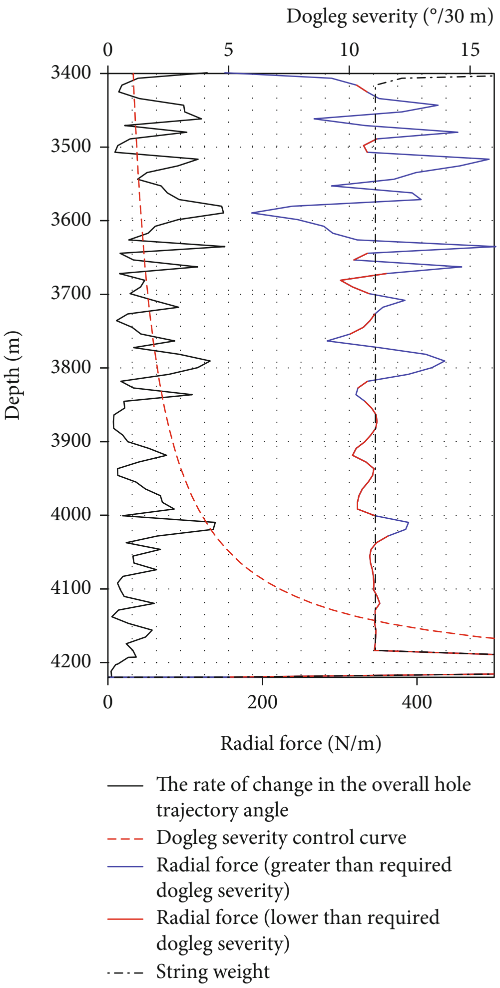

Figure 7: Distribution of whole radial force in the horizontal section of a horizontal well during tripping out.

severity ϑ should be controlled within 1° at point A, within 2° at 500 m, and within 3° at 610 m in horizontal section.

4. Results and Discussion

4.1. Case Study. Taking the case well in Figure 2 as an example once more, the radial force which occurred in the actual drilling is compared with the one predicted in the drilling program, for the vertical section and the horizontal section in Figures 6 and 7, respectively.

It can be seen from Figure 6 that the radial force in the vertical section was supposed to be zero in the drilling program, implying that the predicted radial force would be far from reliable if dogleg severity is ignored. In the figure, the dashed red line represents dogleg severity in the vertical section to be controlled based on Equation (23), and the solid red line represents the radial force in the intervals wherever dogleg severity was lower than the one to be controlled, which was smaller than 350 N/m and roughly equal to the weight of the string. The blue line represents the radial force in the intervals wherever dogleg severity was higher than the one to be controlled, which was quite great and exceeded the weight of the string, with the maximum being greater than 2200 N/m. This example confirms the proposition that it is necessary to control dogleg severity in the vertical section to prevent too high friction and verifies the usefulness of Equation (23).

In Figure 7, the dashed red line represents dogleg severity in the horizontal section to be controlled based on Equation (28) ($b = 0.15$), and the solid red line represents the radial force in the intervals wherever dogleg severity was lower than the one to be controlled, which fluctuated within 15% of the string weight. The blue line represents the radial force in the intervals wherever dogleg severity was higher than the one to be controlled, which fluctuated more around the string weight, with the maximum being greater than 500 N/m and the minimum being only 186 N/m. The problem is particularly severe close to point A in the horizontal section. In general, the fluctuation of the radial force in the horizontal section is lighter than that in the vertical section because the axial load on the string is much smaller in the former case. Therefore, from the perspective of friction reduction, dogleg severity in the horizontal section can be less strictly controlled in comparison with the vertical section, such as being kept lower than 2°/30 m, but a higher dogleg severity might lead to sticking of the drill string.

4.2. Discussion. According to the analysis above, the gravity and tension radial forces are the dominating factors giving rise to friction. Bending radial force gives rise to minor friction in medium- and long-radius horizontal wells. Calculation results can be seen from Table 1. At dogleg severity of 5°/30 m, the bending radial force of the drill collar is only 13.1% of the weight of the string.

Tension radial force, an important factor affecting drilling friction, can be reduced by improving the smoothness of the wellbore trajectory. A criterion was put forward in this paper which states that dogleg severity in the vertical section should be controlled so that in the curved section, the gravity radial force exerted by the string does not exceed its weight. Later on, the criterion might be perfected to make it even more reliable. Experiences tell us that friction in the building and horizontal sections will be small if dogleg severity in the vertical section, especially in the upper part of this section, is controlled lower than 0.5°/30 m. Tension radial force gets smaller in the building and horizontal sections. However, considering the increase of the string weight, the tension radial force should be further controlled (an appropriate ratio b value, i.e., the ratio of tension radial force to the weight of the string, is to be controlled) in order to prevent massive increase of the radial force. Generally speaking, dogleg severity should be less than 2°/30 m in a horizontal section longer than 1000 m to facilitate subsequent drilling operations.

5. Conclusions

(1) The radial force of the string is analysed, and the calculation models for computing the friction in the vertical and horizontal sections were also established. The case study shows that the radial force may arise in the upper part of the vertical section. The bending

radial force is within 13.1% of the string weight if dogleg severity is lower than 5°/30 m

(2) Tension radial force and gravity radial force are the main factors influencing the friction in horizontal wells. In order to reduce the friction, it is necessary to control the tension radial force, that is, to control dogleg severity of wellbore trajectory

(3) The equations for controlling dogleg severity in vertical and horizontal sections of horizontal wells was were established. The analysis of a case well shows that (1) the deeper the vertical depth of horizontal wells, the greater the add-on factor for the tension radial force; as a result, dogleg severity in the upper part of the vertical section of deep horizontal wells has to be controlled more strictly. For example, if the additional coefficient of string tension is 0.5 for the vertical horizontal well of 3000 m, dogleg severity at 1000 m should be controlled within 0.5°/30 m, and dogleg severity of the vertical well section at 1000~2000 m should be controlled within 1°/30 m. (2) Dogleg severity of the maximum angle in a horizontal section is inversely proportional to the friction in the subsequent section. The closer to target A, the higher the requirement for dogleg severity, which can be appropriately reduced in subsequent wells. If the ratio of tension radial force to weight of the string, b, is to be controlled at 18%, L_h is 1000 m, and μ is 0.3, then dogleg severity ϑ should be controlled within 1°/30 m at target A, within 2°/30 m at 500 m, and within 3°/30 m at 610 m in horizontal section

(4) The model of friction prediction considered the influence of dogleg severity, and the conclusions given are valuable for long displacement horizontal well drilling especially in unconventional oil and gas field. In order to control the radial force and friction of the building section, lower building rate should be adopted in the early building section, and appropriately higher building rate can be adopted later. Sliding drilling should be practiced less, and combined drilling with lower building rate should be used more. By doing so, the influences of tension radial force and bending radial force will be mitigated. This conclusion can help improve bit efficiency and reduce drilling costs

Data Availability

No underlying data was collected or produced in this study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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